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# SHADOW EFFECTS ON A SERIES-PARALLEL ARRAY OF SOLAR CELLS

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SERIES-PARALLEL ARRAY  
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ABSTRACT

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Curves have been obtained to illustrate the effect of shadowing solar cells in a series-parallel solar cell array. Measurements of the degradation of the voltage-current curve and the power at a suitable operating point as a function of shadowing were made on a 48 by 8, series-parallel solar cell array for shadowing of series, parallel and series-parallel combinations. The results of the experiment are illustrated to provide a basis for extrapolation to any shadow-array configuration.

*Author*

## SUMMARY

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Satellite solar arrays are subjected to shadowing by booms, antennas, solar paddles and the satellite itself. The effect of shadows is primarily a power loss and is dependent on the shadow geometry and the solar array geometry. The losses vary considerably depending on whether, and how many, series or parallel cells are shadowed and can cause serious problems for the power-conditioning system.

Voltage-current curve measurements were made on a 48 by 8 solar cell array under various shadow configurations ranging from shadowing of a single cell to shadowing of a 16 by 4 cell section. The various families of curves obtained provide a basis for extrapolating to any shadow-array configuration.

The measurements clearly show that shadowing of parallel cells is far more detrimental than shadowing of series cells to the extent that almost total power loss can be expected when a single parallel row is shadowed. Shunting effects of shadowed cells were readily observed and result in excess power loss when only a few series cells are shadowed.

Based on the results of these measurements, it is recommended that investigation of the use of by-pass diodes and the understanding of low-voltage "zener-effect" cells be pursued.

*Author*

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# SHADOW EFFECTS ON A SERIES-PARALLEL ARRAY OF SOLAR CELLS

by  
Ralph M. Sullivan

## I. INTRODUCTION

Shadowing of the solar cell array is an important consideration in the design of present satellite power supplies. The most obvious result of a shadow is a decrease in power output from the solar array. The amount of power loss is a function of the size and shape of the shadow, the geometrical and electrical layout of the cells in the array, and how the shadow falls across the particular solar cell array.

Solar arrays on spin-stabilized satellites are subject to an additional complication. Due to the rotation, fast-sweeping shadows of the satellite extensions (booms, antennas, solar paddles, and the satellite itself) cause sharp variations to occur in the available power in relatively short periods of time. This can cause the spacecraft voltage to alternate abruptly between the battery charge voltage and the battery discharge voltage. Thus, an unstable voltage source is presented to the power conditioning equipment.

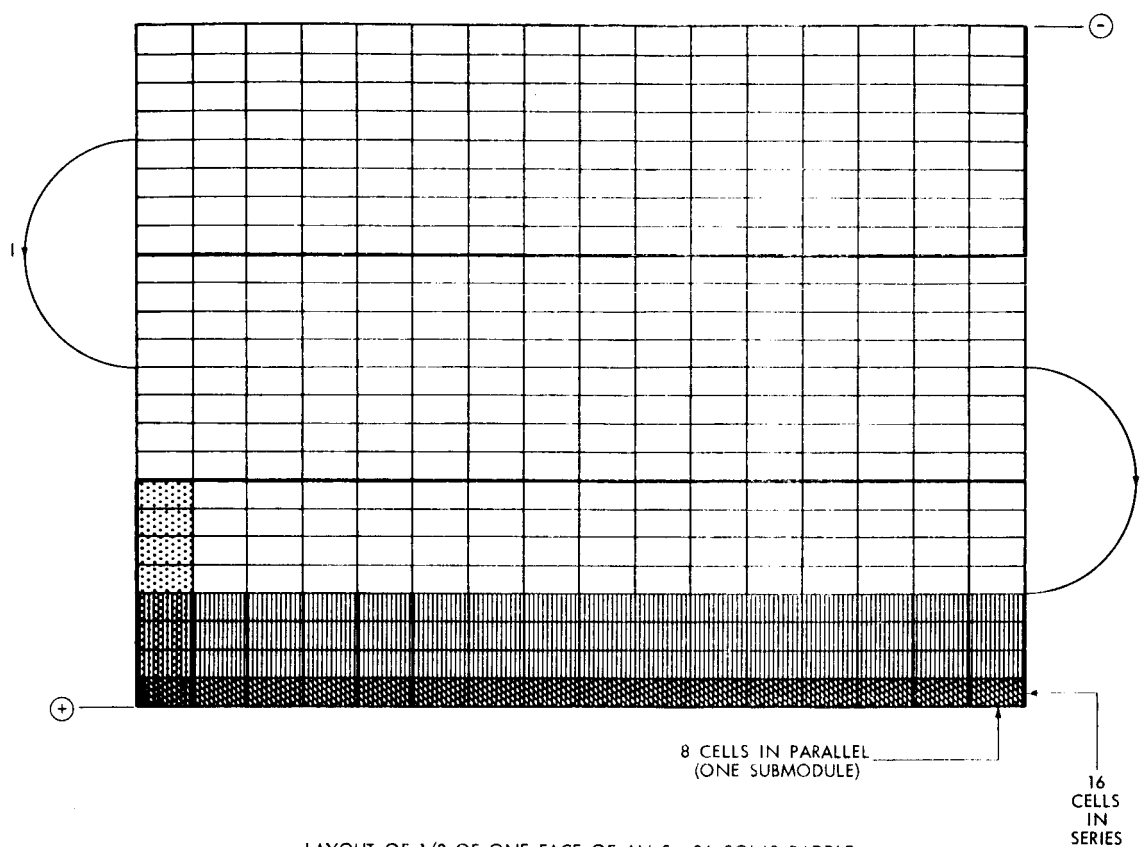
Finally, systems are now being considered which search the E - I curve of the solar cell array periodically to determine the optimum bias point for maximum power delivery to the spacecraft. To properly design such systems, it is necessary to consider the E - I curve of the solar array under all operational conditions. Since shadowing causes a peculiar distortion of the E - I curve, it is necessary to include this case in the considerations.

This report presents experimentally determined effects on the voltage-current characteristic of a typical series-parallel array of solar cells when certain basic combinations of cells are shadowed. These combinations were chosen so that the results could be expanded to represent the effects of almost any general shadow form.

## II. METHOD OF MEASUREMENT


Figure 1 shows a layout of the particular array on which the measurements were made. Included are specific data on this array and definitions of some of the terms used in the following discussions. E - I curves were obtained for the






LAYOUT OF 1/2 OF ONE FACE OF AN S - 3A SOLAR PADDLE  
(48 BY 8 SERIES - PARALLEL ARRAY)

PADDLE MANUFACTURER - SPECTROLAB  
CELL MANUFACTURER - HELIOTEK  
TYPE OF CELL - P/N, GRIDDED, FLAT MOUNTED  
SIZE OF CELL - 1 x 2 cm

 PARALLEL CELLS WHICH WERE SHADOWED SUCCESSIVELY

 SERIES CELLS WHICH WERE SHADOWED SUCCESSIVELY

 1/2 - SUBMODULES WHICH WERE SHADOWED SUCCESSIVELY

Figure 1. Layout of the Series-Parallel Solar Cell Array  
Showing Examples of the Shadowed Areas

entire group of solar cells under various shadow conditions. All curves were obtained on an X - Y plotter which was calibrated to within 1%. The light source consisted of twenty-five 300-watt tungsten bulbs, filtered by 3 cm of water and 1/2 inch of plexiglas. The bulbs were arranged in a square (5 by 5) array to illuminate the test area. Both the voltage and orientation of the bulbs were adjusted to give uniform illumination in the test plane. The uniformity was determined with a 1 by 2 cm standard solar cell and measured to be within  $\pm 5\%$ . To adjust the intensity, the array was placed in the test plane and its distance from the light source was adjusted so that the short circuit current of the array was the same as it would be under  $100 \text{ mw/cm}^2$  of sunlight. Successive adjustments for uniformity and intensity were performed since a change in one had a slight effect on the other. No attempt was made to control the color temperature of the bulbs, since it was necessary to adjust the operating voltage to aid in obtaining uniform illumination. The temperature of the array was held to  $32 \pm 2^\circ\text{C}$  by forcing air across it. The shadowing was accomplished by placing heavy black felt cloth directly over the cells to be shadowed.

### III. SHADOWING OF PARALLEL CELLS

#### 1. Shadowing of a Complete Parallel Row (Submodule)

Figure 2 is a set of curves illustrating the effect on the E - I curve of the entire cell array when one complete submodule (eight cells in parallel) is shadowed. Each curve represents the effect of shadowing a different submodule. Superimposed on these curves are two constant voltage lines representing the maximum and minimum bias voltages for the solar array in operation. The 20-volt level is the maximum charging voltage of the silver cadmium battery and the 15.5-volt level is the minimum discharge voltage of the battery under normal operation.

It is clear from these curves that the results vary considerably depending on which particular submodule is shadowed. Curves "d" and "e" are the more typical cases, while curve "a" is relatively unusual. Since curves "d" and "e" illustrate that the power throughout the operating range degenerates to near zero for typical submodules, the common practice of treating a shadowed submodule as an open circuit is reasonable although not entirely correct.

In general, a shadowed cell is not truly an open circuit. There is an added impedance presented to the solar array due to the high resistance of shadowed solar cells. To illustrate this point for a single cell, reference is made to Figure 3. The characteristic curves of three different shadowed solar cells under external voltage bias are shown, illustrating the variations that can be

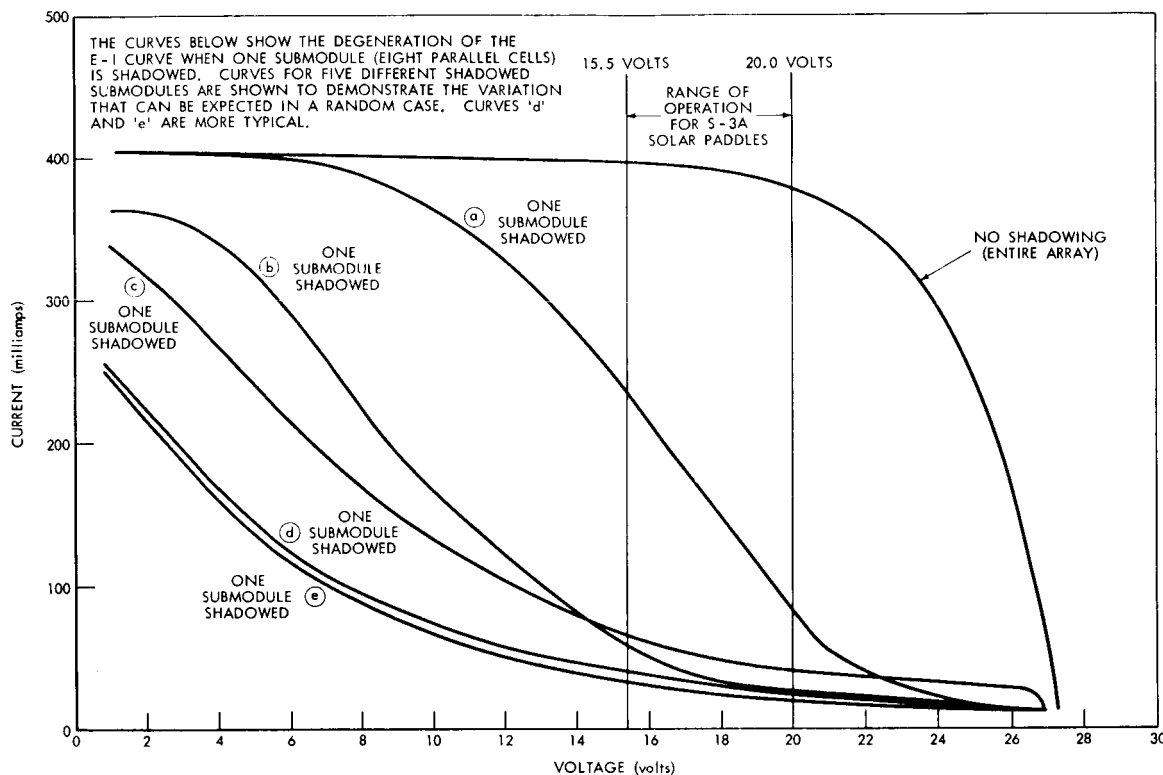


Figure 2. Effect of Completely Shadowing Several Different Submodules (Rows of Eight Parallel Cells)

expected between cells under reverse bias. In general, the reverse characteristic is that of a very poor zener diode and varies considerably from one cell to another. It is this variation which causes the differences in the curves of Figure 2, as will be shown later. Measurements made on n/p and p/n silicon solar cells from three different manufacturers showed that the variations within each cell type were large enough to mask out any differences which could be attributed to manufacturing techniques.

A shadowed parallel row of solar cells exhibits a similar reverse characteristic. As depicted in Figure 4, it presents a reverse bias to the solar array and diminishes the voltage across the load. So that for any given current:

$$V_L = V_I - V_S$$

where

$V_I$  is the voltage generated by the illuminated portion of the array,  
 $V_S$  is the voltage drop across the shadowed portion of the array, and  
 $V_L$  is the voltage available to the load.

If this relationship is applied to curves "a" through "e" of Figure 2, then it is possible to determine the reverse characteristic that the shadowed sub-modules must have. This is done for curve "a" in Figures 5 and 6, and for curve "d" in Figures 7 and 8.  $V_I$ ,  $V_S$  and  $V_L$  are depicted on these curves for one current value (100 ma).  $V_Z$ , in Figures 6 and 8, refers to an apparent zener effect and may be somewhat loosely defined as the voltage at which the "knee" occurs. It is clear that a decrease in  $V_Z$  would consequently decrease  $V_S$  and the distortion of the E-I curve and loss of power due to shadowing would be smaller. It should be pointed out that a reverse characteristic with a low  $V_Z$  (such as the one in Figure 6) can be due to only one cell of the eight parallel solar cells.

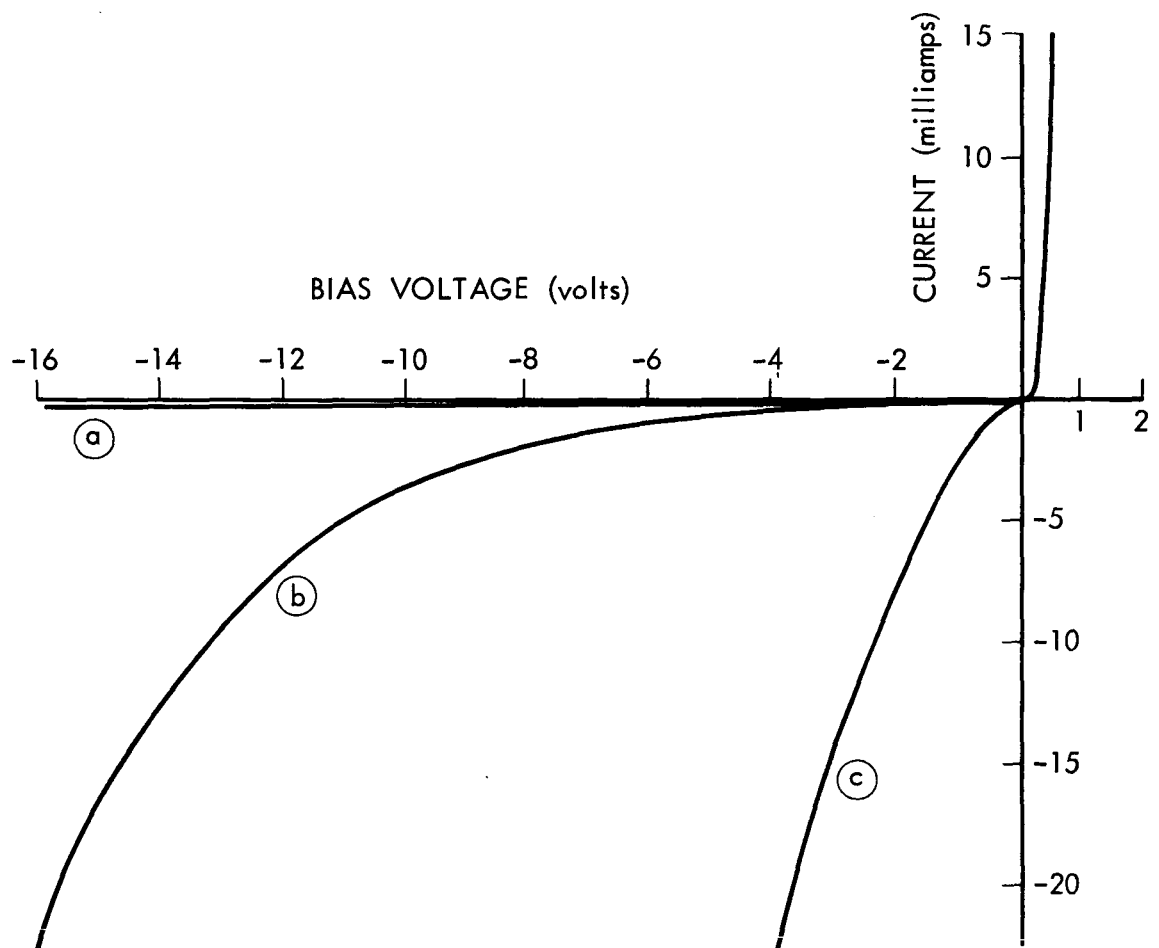


Figure 3. Voltage-Current Characteristics of Shadowed Solar Cells Illustrating the Differences in Reverse Regions

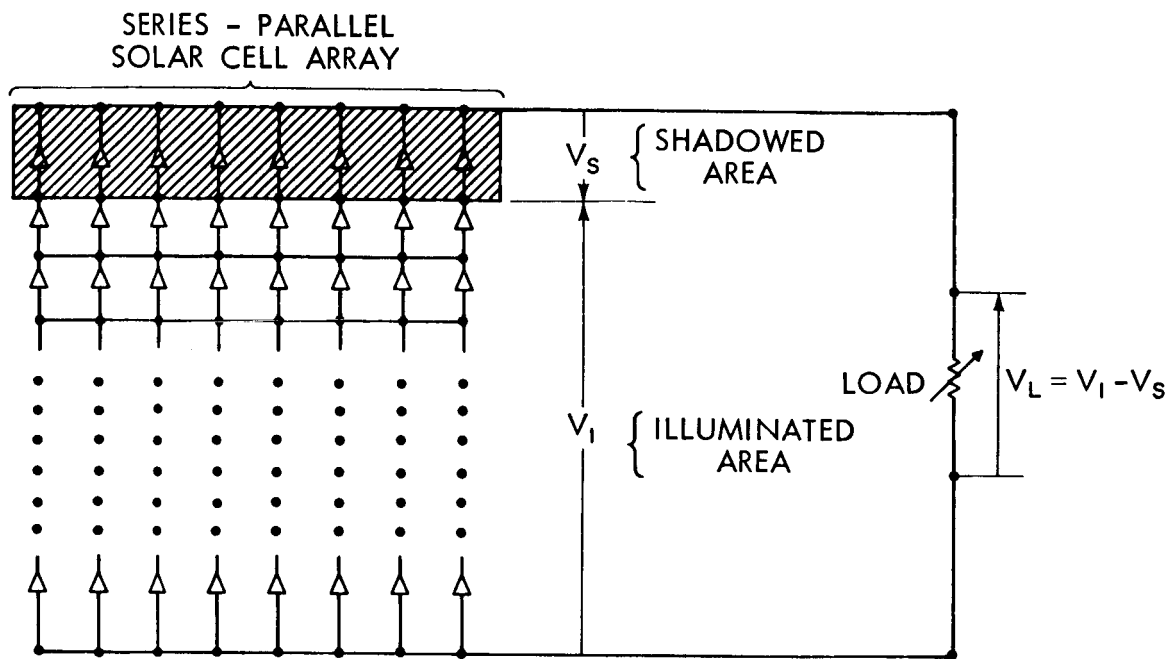


Figure 4. Solar Array Schematic Illustrating the Effect of a Shadowed Submodule

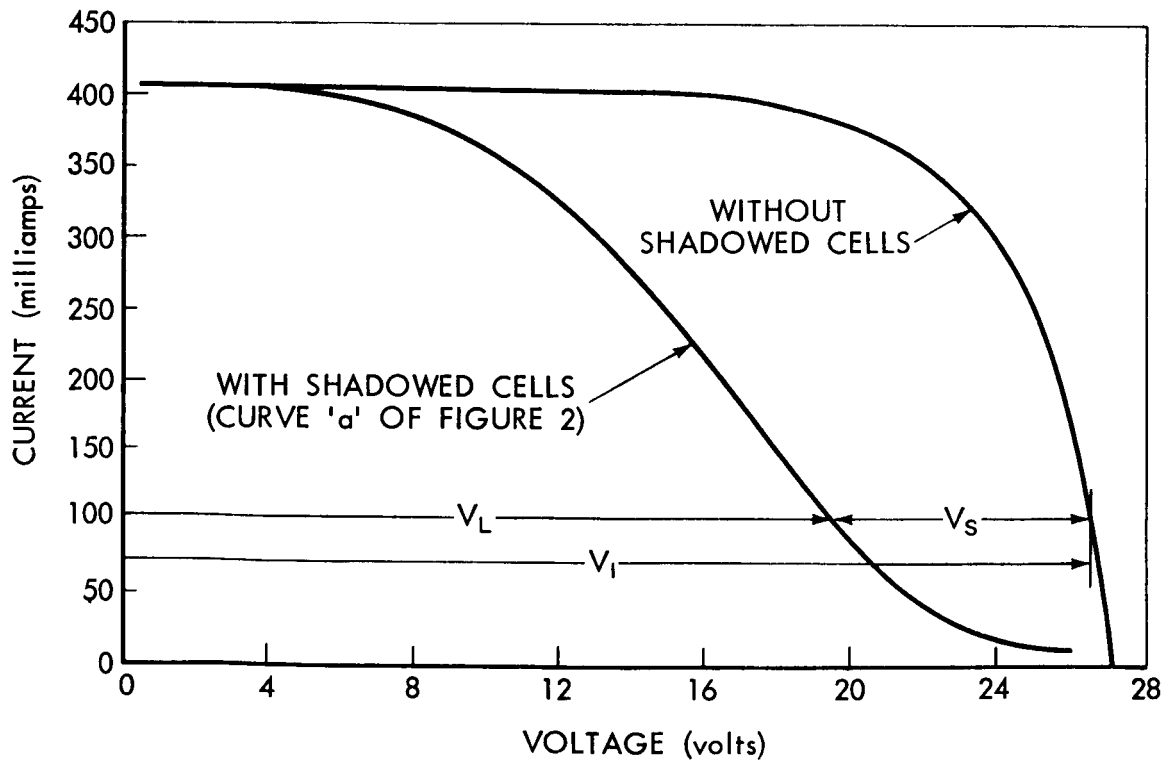


Figure 5. Curve 'a' of Figure 2 Showing  $V_i$ ,  $V_s$ , and  $V_L$  for 100 Milliamps

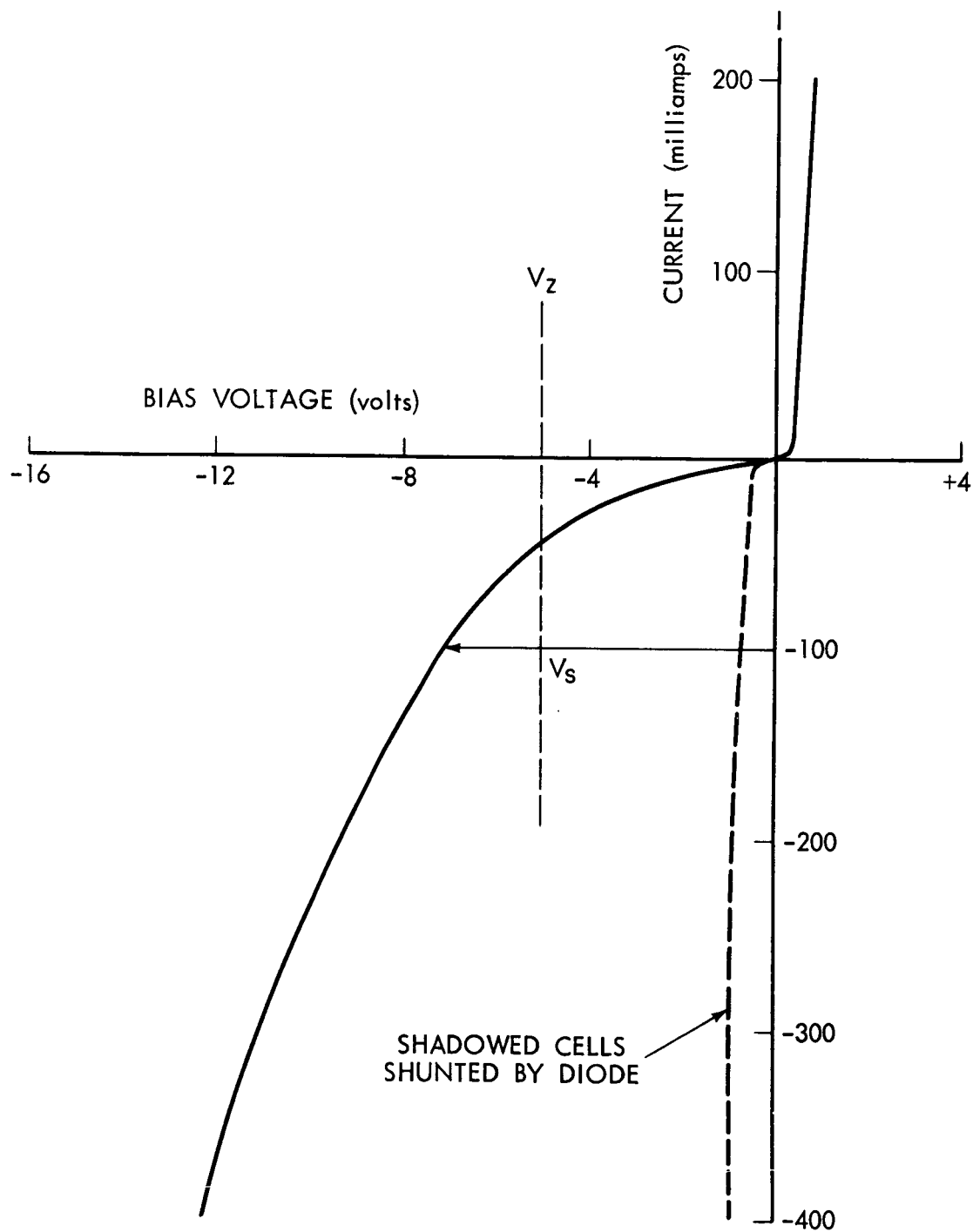


Figure 6. Voltage-Current Characteristic of the Shadowed Solar Cells of Figure 5

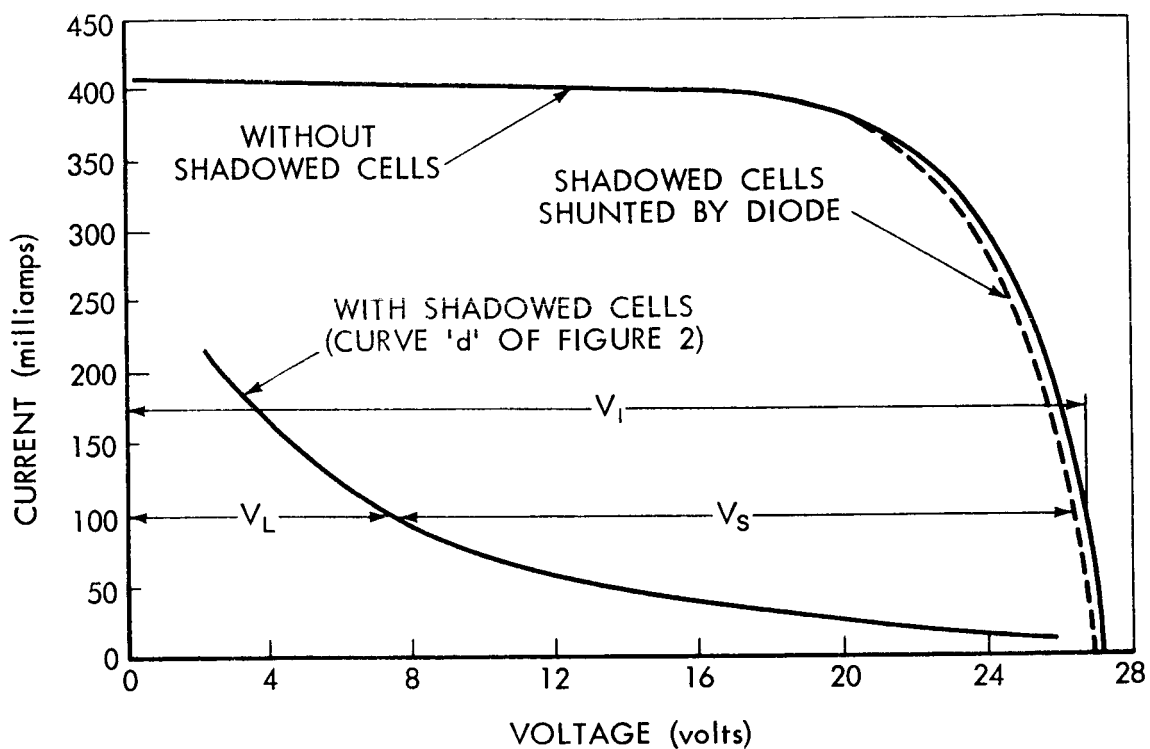


Figure 7. Curve 'd' of Figure 2 Showing  $V_I$ ,  $V_S$ , and  $V_L$  for 100 Milliamps

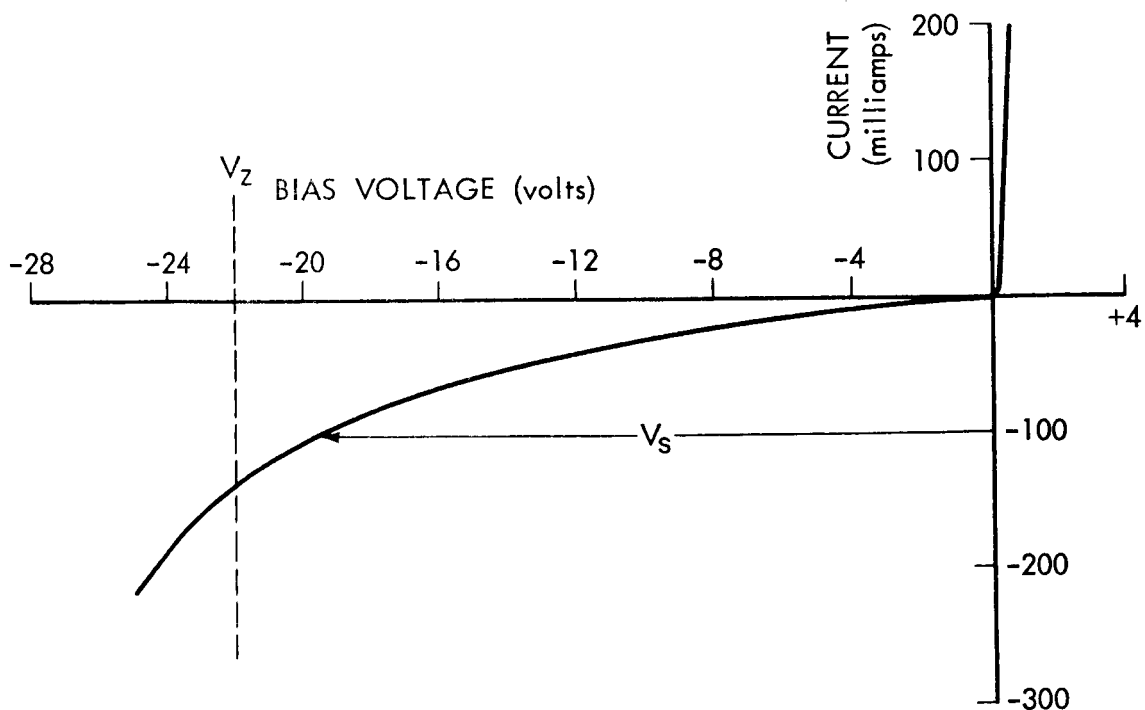


Figure 8. Voltage-Current Characteristic of the Shadowed Solar Cells of Figure 7

## 2. Partial Shadowing of a Submodule

Figures 9, 10, 11, and 12 further analyze curves "a" and "d" of Figure 2. Figure 9 shows the effect on the E - I curve of the entire cell array when a typical submodule (curve "d" of Figure 2) is shadowed in eight different steps with one additional cell shadowed in each step. Figure 10 shows the power degradation in the operating range of 15.5 to 20.0 volts as the cells are shadowed consecutively. In figures 11 and 12, the same is done for a submodule which is not typical (curve "a" of Figure 2).

Figure 10 shows that in the case of the "typical" submodule there is less power loss in the actual case than would be obtained on a direct ratio basis. Figure 12 shows that in the "unusual" submodule there is considerably less power loss than would be obtained on a direct ratio basis and that this power loss is reduced at the lower operating voltage. However, these results apply strictly for the case where only parallel cells are shadowed. Quite the reverse is true when groups of series-parallel cells are shadowed, as will be shown.

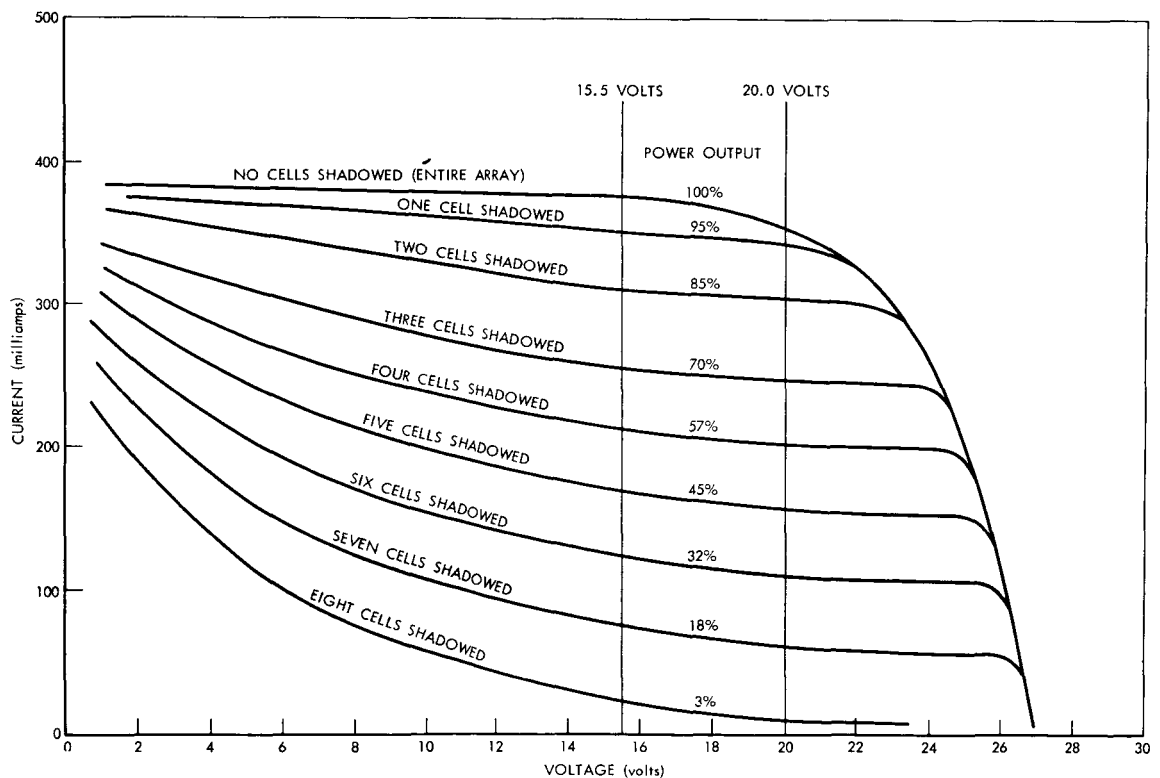


Figure 9. Effect on Total Array Output of Shadowing One Complete Row of Parallel Cells, One Cell at a Time. (The Particular Submodule Chosen Corresponds to Curve 'd' of Figure 2)



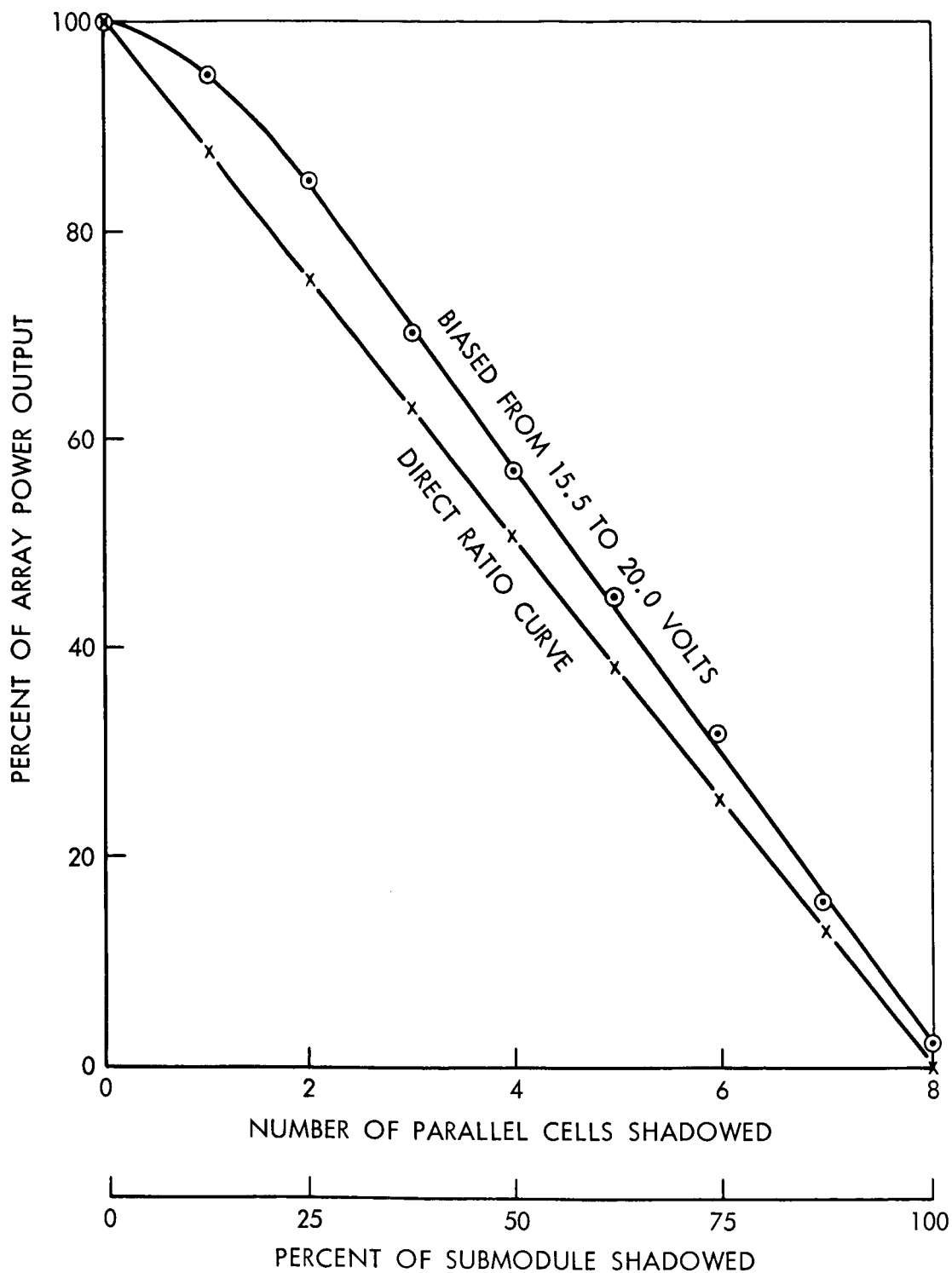


Figure 10. Percent of Array Power Output (Between 15.5 and 20.0 Volts) as a Function of Shadowed Area on the Submodule of Figure 9

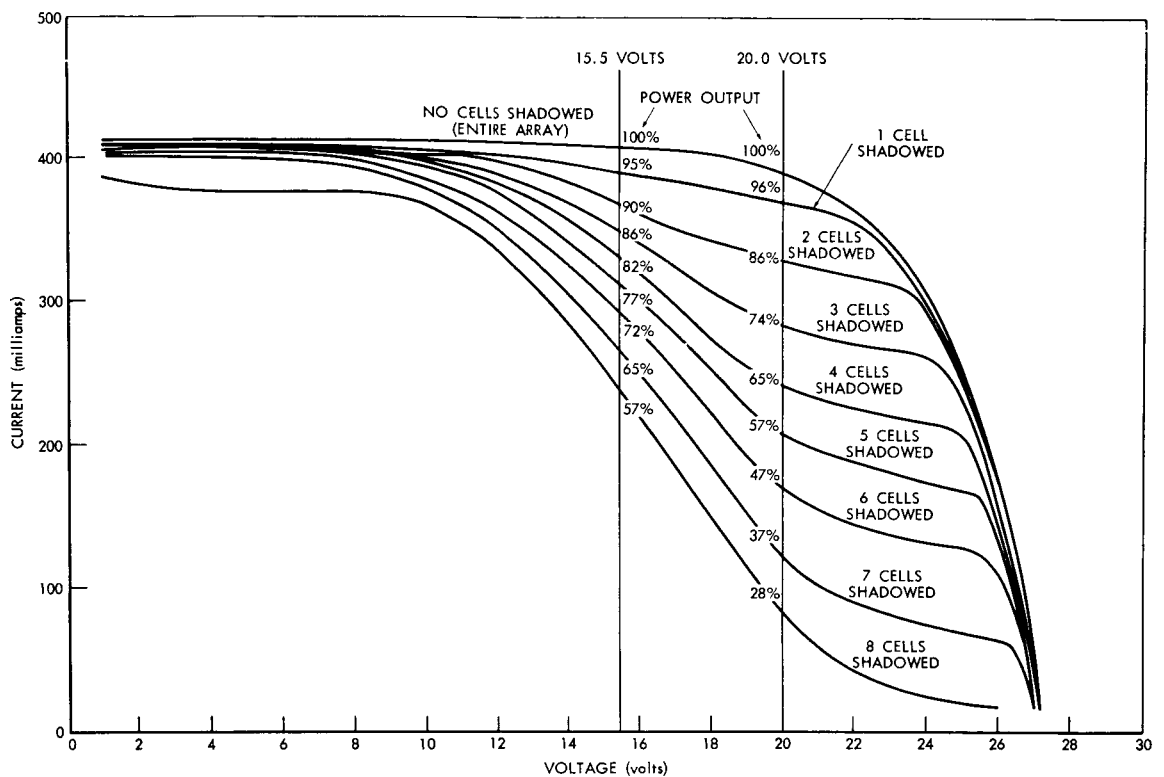


Figure 11. Effect on Total Array Output of Shadowing One Complete Row of Parallel Cells, One Cell at a Time. (The Particular Submodule Chosen Corresponds to Curve 'a' of Figure 2)

#### IV. SHADOWING OF SERIES CELLS AND SERIES SUBMODULE FRACTIONS

Figure 13 shows the effect on the E - I curve when 16 cells of different, single, series strings are shadowed. Only 16 of the 48 cells in series were shadowed because of practical difficulties involved in shadowing the complete series string (see Figure 1). A reasonable extrapolation to the complete string of 48 cells can be made (Figures 14 and 15) neglecting the leakage current loss through the shadowed solar cells. It should be emphasized that the shadowed cells in this case do not need to be in one straight line (as depicted in Figure 1) to produce the same effect. Due to the series parallel interconnections, they can be distributed over the array (diagonally, for example). The only restriction is that no shadowed cell is in parallel with any other shadowed cell. Figure 14 shows the effect of shadowing different numbers of cells in the same series string and the effect of shadowing different numbers of half-submodules (4 cells in parallel) in the same four series strings. Figure 15 shows the percent power degradation for the cases illustrated in Figure 14.

From these curves it is clear that, in a series string, most of the power degradation takes place due to the first few shadowed cells, and that the power

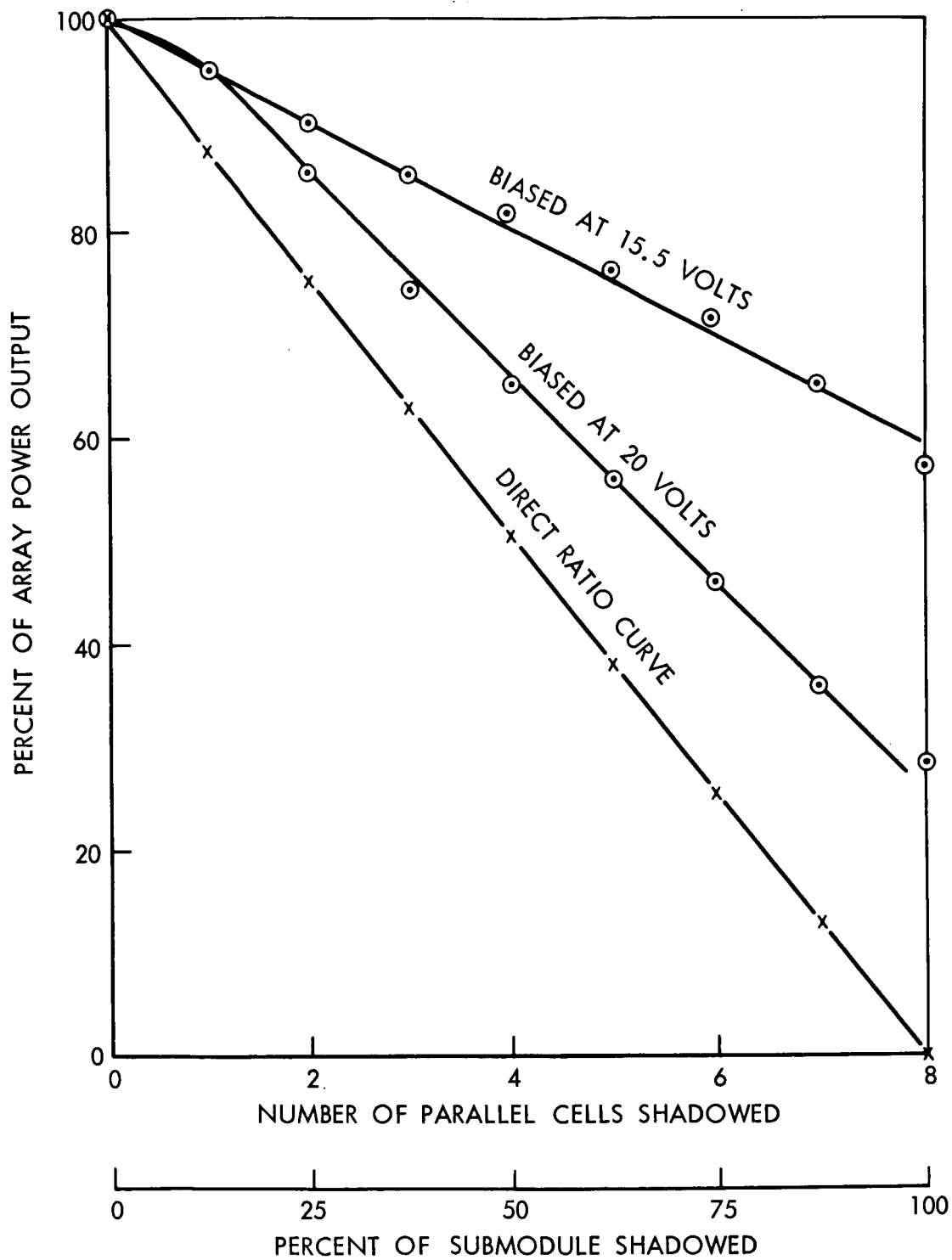


Figure 12. Percent of Array Power Output (Between 15.5 and 20.0 Volts) as a Function of Shadowed Area on the Submodule of Figure 11

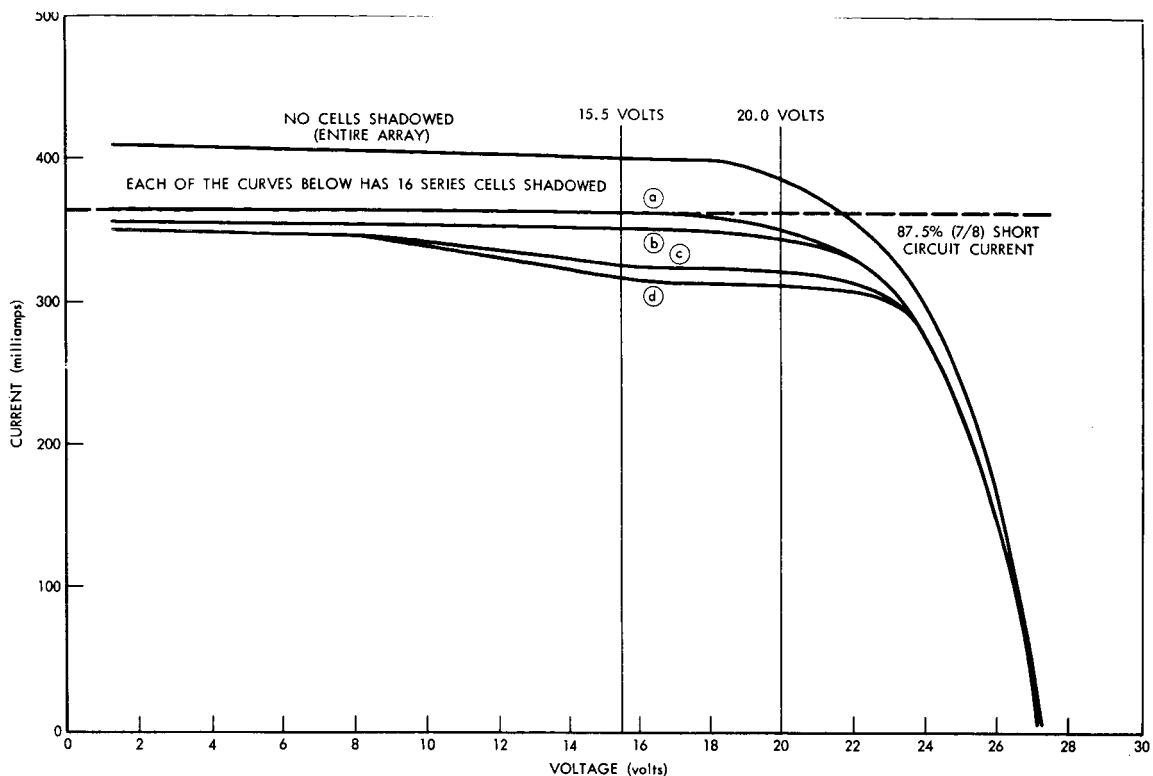


Figure 13. Effect on Total Array Output of Completely Shadowing Several Different Strings of 16 Series Cells

also will drop below 87.5% (7/8) of the initial power when one string becomes shadowed, and below 50% (1/2) of the initial power when four strings become shadowed. Furthermore, Figure 14 shows that the short circuit current drops below 87.5% of the initial short circuit current when one string becomes shadowed and below 50% of the initial short circuit current when four strings become shadowed. The values of 87.5% and 50% would be obtained on a straight percentage basis if these strings were looked upon as simply independent open circuits. This excess loss can be explained in the following manner. From the conventional simplified equivalent circuit, shown in Figure 16, it can be seen that the shadowed cell, when connected in parallel with other illuminated cells, will act as a forward biased diode with a series resistor ( $R_S$ ). Figure 17 shows how this occurs in an array of cells. Hence, the shadowed cells not only add impedance in the array, but also drain power (through the diode shunting action) from the illuminated cells in parallel with them. These results emphasize the value of blocking diodes between groups of cells where some are illuminated and some are not.

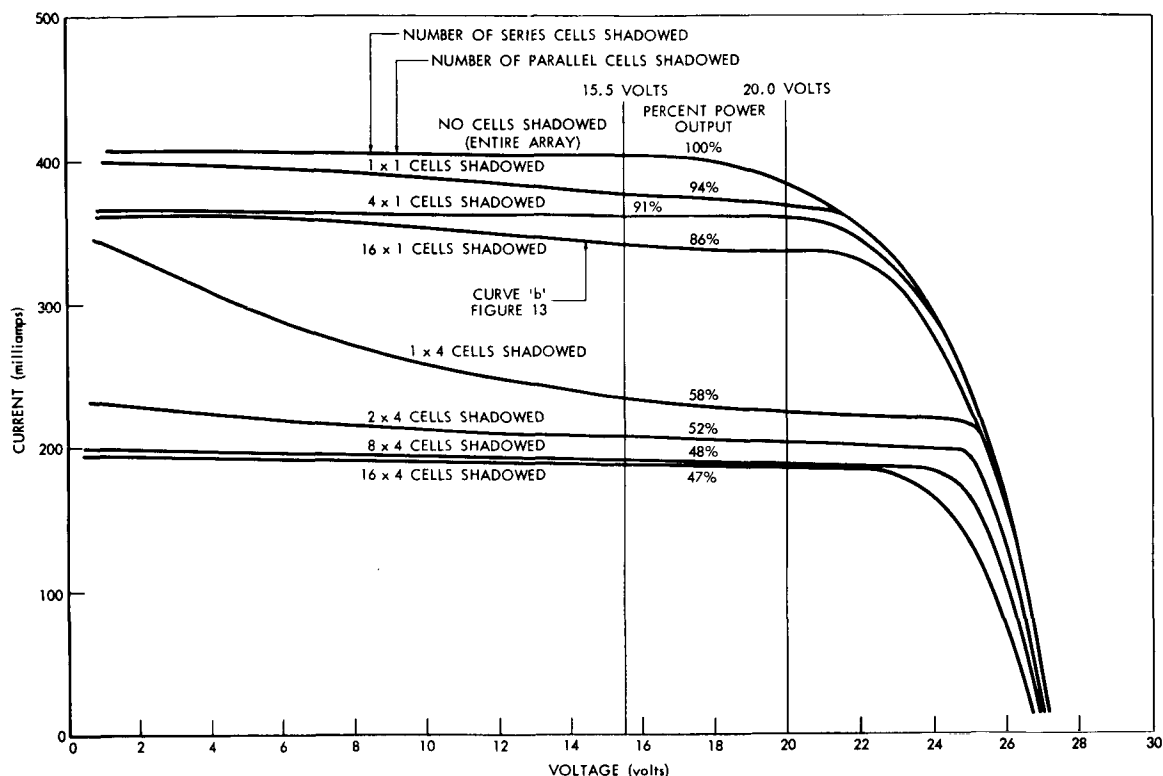


Figure 14. The Effect of a Shadow which Covers Different Numbers of Cells in Series and Parallel

## V. CONCLUSIONS

The investigation of the effects of shadowing on a series parallel solar cell array leads to the following conclusions:

1. Curves which depict the effect of shadowing of various series-parallel cell combinations in a series-parallel solar cell array were obtained. These curves can be used to estimate the effects of arbitrary shadows on any solar array.
2. There is considerable variation in the power loss due to shadowing of a complete parallel row of cells. The variation is due to large variations in the reverse characteristics of individual cells. The variations are independent of manufacturer.
3. For the most part, the power loss due to shadowing of a complete parallel row is almost 100% because of the high impedance of the shadowed cells and, therefore, for practical application the effect should be treated as an open circuit.

THE DASHED LINE ON THE CURVES BELOW IS AN EXTRAPOLATION WHICH NEGLECTS THE EFFECT OF CURRENT DRAIN THROUGH THE SHADOWED CELLS.

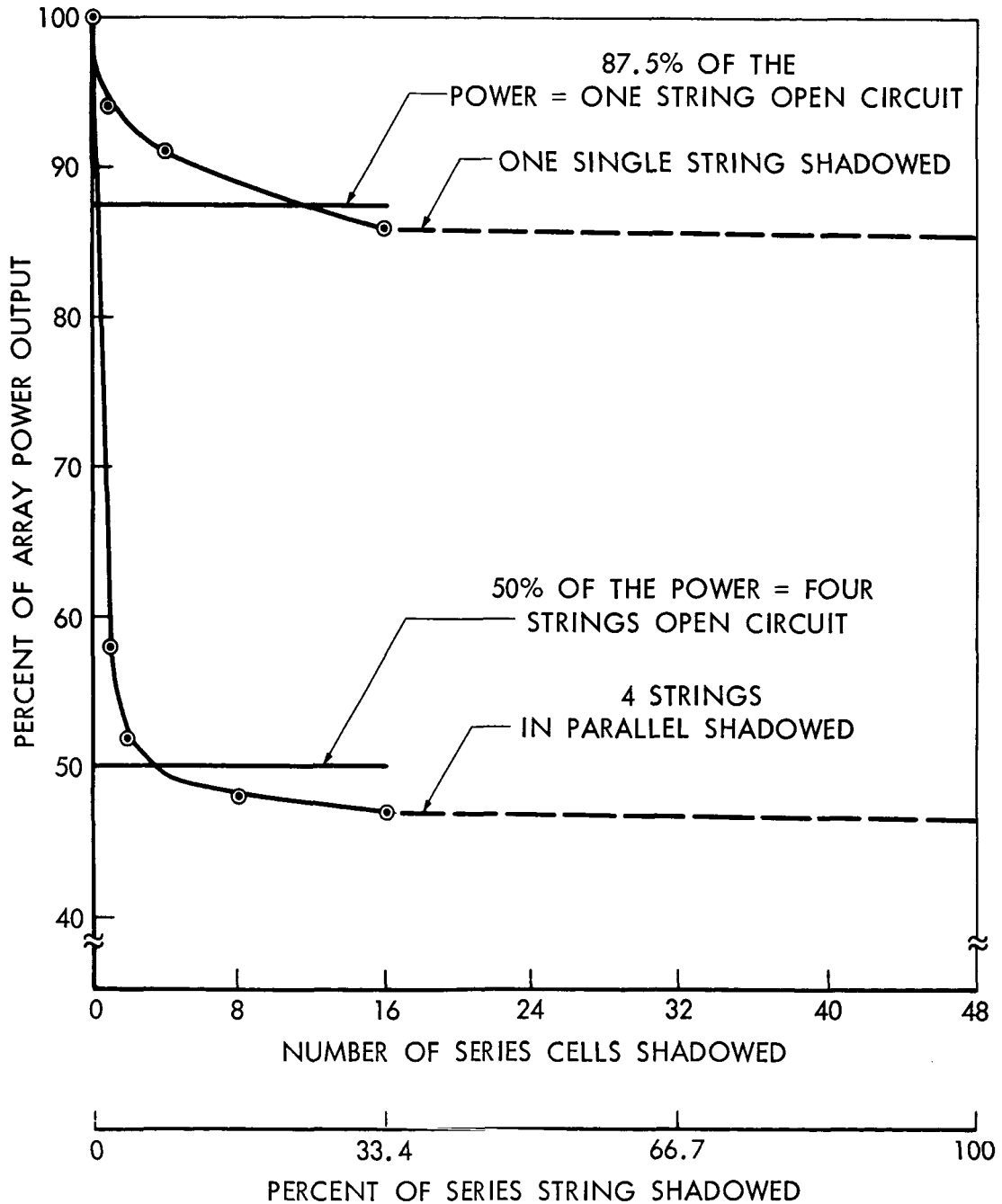


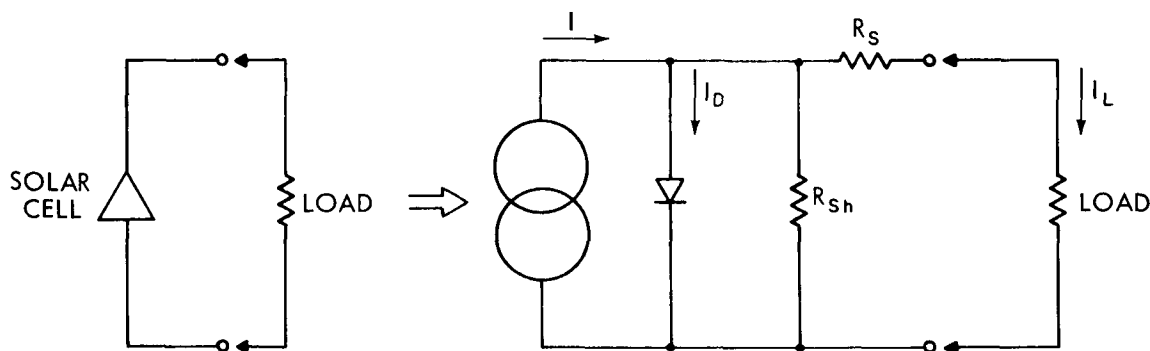
Figure 15. Percent of Array Power Output (Between 15.5 and 20.0 Volts) as a Function of Shadowed Area

4. For the typical submodule when partial shadowing of a single parallel row of cells occurs, the power loss is only 5 to 10% less than that computed on a percent shadow basis. Nontypical submodules in which low-voltage zener effects are apparent were found. The power losses associated with the shadowing of these submodules were significantly less than those of the typical submodules and are highly voltage-dependent.

5. The power loss associated with shadowing one or more complete series strings is significantly greater than would be computed on a percent shadow basis because of the shunting action (due to the diode characteristic) of the shadowed cells. This loss is approached rapidly. For example, in the eight-string group of cells investigated, it was found that:

- a. When shadowing occurs on a single series string (1 out of 8), one-eighth of the total power was lost when less than 25% of the cells in the one string were shadowed.
- b. When shadowing occurs on half of the series strings (4 out of 8), half of the total power was lost when less than 10% of the cells in the four strings were shadowed.

6. The excess power loss due to the shunting action of the shadowed cells emphasizes the need for blocking diodes between shadowed and illuminated cells.



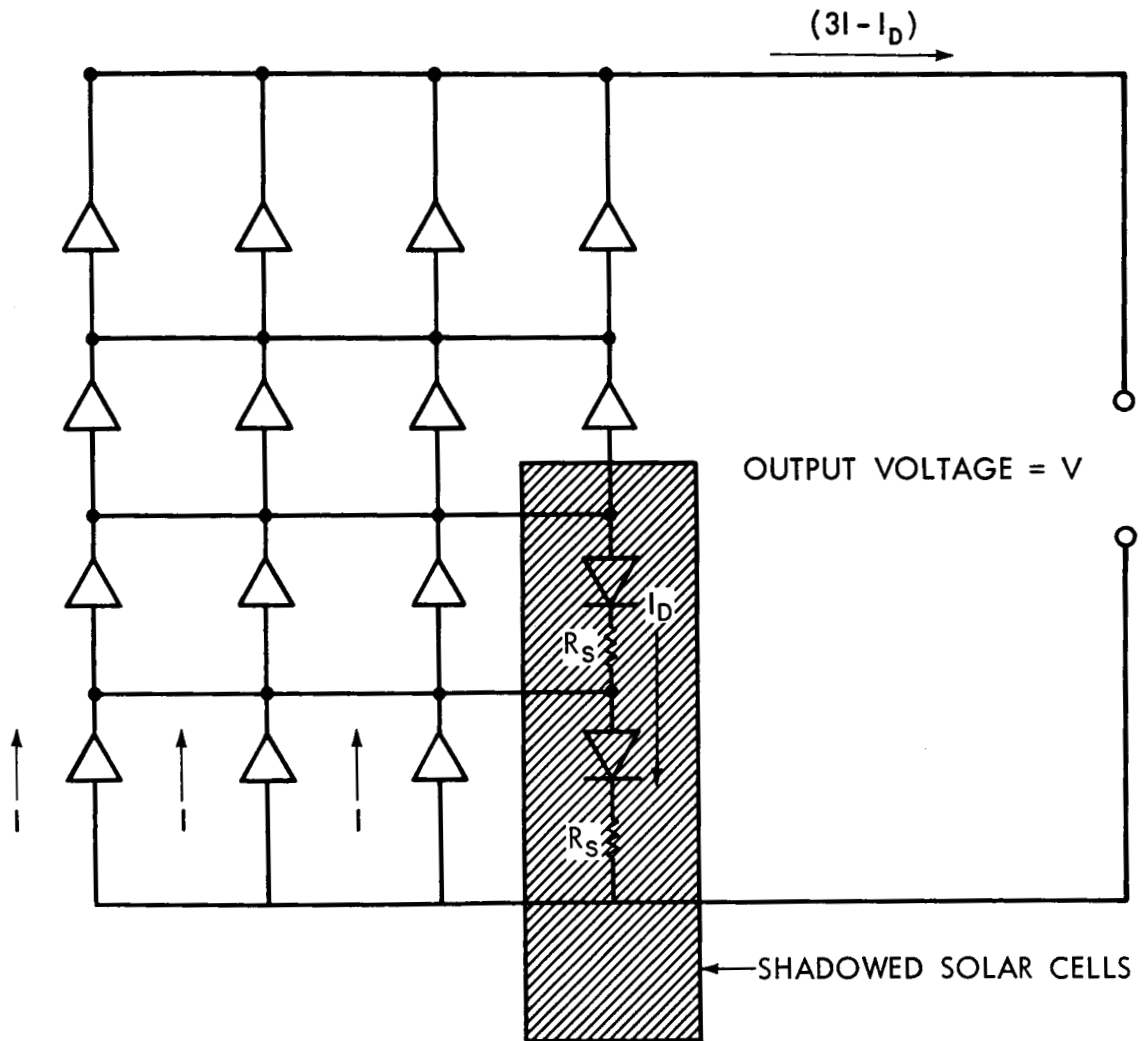
$I$  = CURRENT OUT OF CONSTANT GENERATOR  
(THIS IS THE SHORT CIRCUIT CURRENT AND  
IS DIRECTLY PROPORTIONAL TO THE LIGHT  
INTENSITY).

$R_s$  = THE SERIES RESISTANCE OF THE CELL.

$R_{sh}$  = THE SHUNT (LEAKAGE) RESISTANCE OF THE  
CELL WHEN IT IS REVERSE BIASED.

Figure 16. Simplified Equivalent Circuit for a Solar Cell

7. The layout of solar arrays should be designed so that most of the shadowing occurs along series rather than across parallel cells to minimize the power loss due to shadowing.



$I$  = CURRENT FROM ILLUMINATED CELLS.

$I_D$  = CURRENT DRAIN THROUGH SHADOWED SOLAR CELLS.

$R_s$  = SERIES RESISTANCE DEPICTED IN FIGURE 16.

Figure 17. Illustration of Shaded Solar Cells Acting as Forward Biased Diodes to Drain Power from Illuminated Solar Array



## VI. RECOMMENDATIONS

Even though cell layout will undoubtedly remain the most important method of dealing with the shadowing problem, it is not anticipated that a single design can be optimized for all of the expected shadows on a single satellite. The best that can be done is to design for the larger and/or more commonly occurring shadows. After a design has been optimized in this manner, it would be desirable to minimize other shadowing effects which are still prevalent. When these shadows cut across parallel rows (particularly if they are long, thin shadows), the following possibilities exist and should be investigated.

It has been suggested on several occasions and by several sources that a diode be added in parallel with each row or several rows of parallel cells. This is a very promising design concept and should decrease the power loss to an almost negligible amount as shown by the dashed curves on Figure 7 and result in a substantial improvement. The basic reasons that it is not done almost universally are that: (a) adequate experimental information showing the value of this concept is not available; and (b) it complicates an already delicate solar cell mounting procedure.

Referring again to Figure 3, another possibility is suggested. One selected solar cell with a reverse characteristic of equal or lower voltage than curve "c" could be placed in each parallel row. This would not be as effective as adding a diode, in maintaining the I - V characteristic of the array, but would reduce the shadowing effect, as can be seen by comparing Figures 5 to 7.

In addition, the present fabrication techniques should not be complicated in any way beyond the additional requirement of measuring the reverse characteristics of the solar cells. However, since very little is known about solar cells beyond the current and voltage generating characteristics, the characteristics of this particular type of cell should be completely and thoroughly investigated before it is considered for solar array design.